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A study on magnetic field assisted laser percussion drilling and its effect on surface integrity

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ABSTRACT

Purpose: of this paper is to reduce the taper angle and surface roughness of the laser drilled hole on Aluminium alloy with the assistance of magnetic field. At lower laser powers, able to achieve higher material removal rate in drilling with reduced taper angle and roughness.

Design/methodology/approach: Aluminium alloy is a highly reflective material, while laser drilling it ejects plumes, which makes the drilling unreliable. The plume generated due to this action causes deteriorating effects over the work piece as such affecting surface textures. Removal of plume is the major consideration in laser machining process, especially in laser assisted drilling. The plume is a form of cluster of ions having charges in it. Due to the magnetic field input, the ions line the path along the lines of force of magnets. Thus, the ion cloud can be cleared at the localized plane, where the subsequent laser drilling going to be happens, leads to reduced plume thereby reduces the taper angle and surface roughness.

Findings: The defect of percussion laser drilling that is barrelling effect in the drilled hole was reduced with the assistance of magnetic field setup. For the laser energy of 90 mJ, the magnetic assisted laser drilling shows better improvement in the material removal rate of 64.5%, the profile error (spatter height) was reduced to 45% and the taper angle of the drilled hole also reduced by 16.3%. The results confirmed the fact that, the Lorentz force confined the plume particle to be raised upwards and circulated outwards to the sidewall from the centre of the laser beam. This expansion of laser induced plasma plume, improved the material removal rate of the hole.

Research limitations/implications: Laser drilling was carried out by a constant magnetic field and the parameters like material removal rate, taper angle, profile error, surface roughness were studied. In the future work, these parameters were studied with the application of varying magnetic field.

Practical implications: As a result of the work, laser drilling was carried out on turbine blades or complex shapes for retention properties, with reduced taper hole and surface roughness, thereby improving the efficiency of the systems.

Originality/value: The novelty of the work is providing magnetic flux for the laser drilling process, which improves the process parameters. The incorporation of magnetic field to the laser drill needs a cost less setup, which can ensure reliable improvement in the material removal rate, reduction in taper angle and profile error.

Keywords: Laser drilling, Magnetic flux, Plumes, Taper angle, Surface roughness

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Laser percussion drilling has a wide range of potential industrial applications and can accurately process various materials at high operating speeds [1]. The percussion drilling process with ultra-short laser pulses in silicon, which acts as a model system for drilling opaque materials like metals. The investigations are focused on three parts: The role of re-deposition of ablation particles inside the hole which can be reduced by the reduction of the ambient pressure and results in an increased achievable depth [2], the influence of the repetition rate to analyse the heat accumulation effect [3], which increases the achievable depth despite a possible particle shielding, and the effect and evolution of the laser generated plasma [4]. When high requirements concerning machining quality are demanded, ultra-short pulsed lasers with pulse durations from a few 100fs to 10ps may be the tool of choice. For these pulses it is known that the removal rate and machining quality slightly increases with shorter pulse duration [7]. Yuan-Jen et al. (2012), conducted magnetic assisted laser drilling on Al 6061. They examined the effect of both machining efficiency and inlet diameter. The Lorentz force created by the assisted magnetic field influences the laser-induced plasma, which results in enhancing the performance of laser machining. With a proper arrangement of the static magnetic field, the machining depth can be increased by 266%, and the inlet diameter can be reduced by 42%. With a rotational dynamic magnetic field, both the roundness of the inlet and the HAZ can be improved. The deepest hole occurred with the pair of three magnets. With the pair of four magnets, the magnetic strength at the spot of machining was measured to be less than with three magnets, resulting in a shallower hole. The diameter and depth were not effectively improved with the increased spinning speed. It was due to the non-uniform distributed magnetic field between the driving and driven sets resulting in an unstable rotation of the single pair of assembled magnets [10]. Satapathy et al. (2013), conducted the experimental investigation using the Taguchi technique to optimize the machining parameters in plane carbon steel specimen. Three controllable parameters such as pulse width, pulse frequency, the average power of the laser and air flow rate were varied to find out the output parameters such as diameter of the hole, aspect ratio and thickness of HAZ using SEM analysis. They found out the hole of high aspect ratio is possible for a pulse width of 500 μs (lowest), pulse frequency of 3 (highest) and with average power of 1.7 W. They concluded that to obtain a better circular shaped hole, the optimized combination of process parameters of pulse width, pulse frequency and assist gas flow rate are: 500 μs, 3 Hz and 5 lit/min. The optimum combination of process parameters for high drilling rate and high aspect ratio is: pulse width 700 μs, pulse frequency 1 and assist gas flow rate 15 lit/min. High productivity and high quality cannot be obtained simultaneously. One has to make a compromise between these two [11]. The inner surface characteristics of micro-drilled holes of fuel injector nozzles were analysed by Shear Force Microscopy (SHFM). The surfaces created by peak energy in the tested range in ultra-short pulsed laser ablation and micro-EDM are considered. The laser ablation technique generates smooth surfaces with a lower machining time [6]. The plume ejection is mainly normal to the substrate, and the ejection angle is independent of the inclination angle [5]. Laser drilling is growing its importance in many industries, especially in the aircraft industry, used to create micro-holes for cooling purposes in turbine blades, where small holes size and quality are required. The laser percussion drilling process presents extremely high speed for high aspect ratio holes [8]. Alumina ceramics which are widely used in microelectronic devices can be drilled by laser [9].

In this study, the surface integrity of laser drilled components is being analysed, that shows the presence of a magnetic field can cause drastic changes in plume ejection there by the surface roughness of the edges of the drilled holes.

2. Experimental study

The type of laser used in this experiment was Nd-YAG solid state laser having a wavelength of 532 nm and pulse width of 6 ns and frequency 10 Hz. The Laser drilling was done under a controlled environment over the specimen of Aluminium-6061, of thickness 1 mm. A 120 mm focal length lens was used for focusing. A permanent bar magnet (NdFeB) of 230 Gauss was placed in the field perpendicular to the direction of charged particles induced in laser drilling. All experiments were done in air without additional process gas. The setup for studying the effect of the magnetic field is shown in Figure 1.

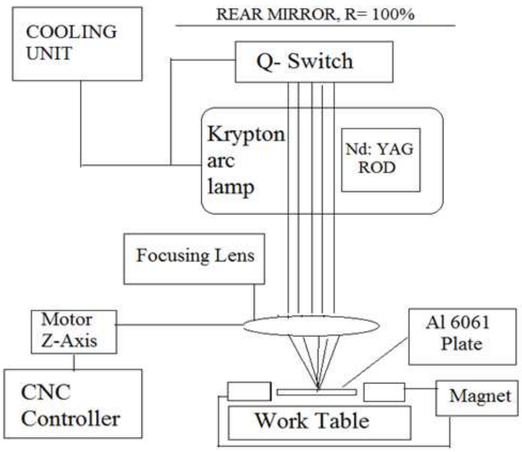

Fig. 1. Setup for studying the effect of magnetic field

In these experiments, the diameter of the holes was determined using optical microscope. The debris height that is the spatter height on the entry side of the hole was determined using a non-contact roughness tester. The quality of the hole was examined by using SEM characterization.

3. Results and discussion

Five laser radiation energies were used for investigating the coupling effect of magnetic field strength on percussion drilling. The profiles, entry and exit diameter of the drilled holes were recorded.

The diameters of the drilled holes were measured using these microscope image techniques. From these diameter values using formulas to determine the MRR, Taper Angle values. The Microscopic image of 40X zooming level shows the Inlet diameter of the laser drilled hole is 241.916 µm and the exit diameter of 70.740 µm for the same output setting in Figure 2 and Figure 3. Thus, the drilled hole having some taper angle between the inlet and outlet hole openings.

Principle: Lorentz force is a combination of electrical and magnetic force. The magnetic field will exert the Lorentz force on the charged ions. It makes the ions to take the path described by that force. The Lorentz force in terms of magnetic field is given by, $F_m = qvB$. This force is equal to the kinetic energy of charged ions given by,

$$F_m = qvB = mv^2r\text{-}^1$$

$$\Rightarrow \quad r = mv/qB$$

where, v – velocity of an electron; r – gyrating radius of an electron; B – applied magnetic field; q – electron charge; m – Electron mass.

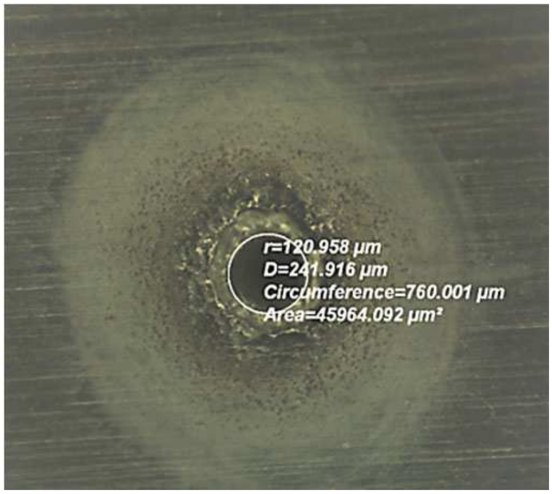

Fig. 2. Optical microscope image of laser drilled hole entry side

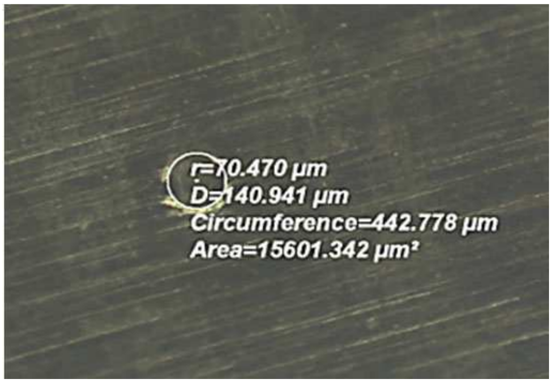

Fig. 3. Optical microscope image of laser drilled hole exit side

The gyrating radius mainly depends on the electron mass that is the amount of charged ions in the plasma plume.

It is observed that MRR increases with the assistance of magnetic field in all laser power used in this experiment (Fig. 4). From these results, it shows compared to laser drilling with and without assistance of magnetic field, the assistance of magnetic field laser drilling takes less time to finish the process. It is observed that the number of pulses increases to drill the hole at a higher energy level. This is due to that material removed from the hole increases with increase in laser energy hence increased MRR. At higher energy level the amount of plasma plume generated is more, it leads to increasing in machining time to complete the process.

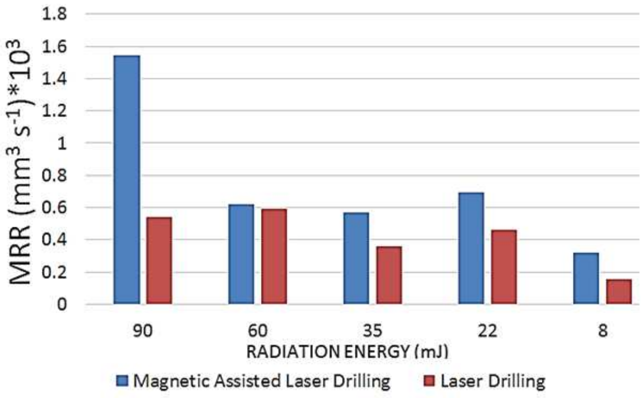

Fig. 4. Comparison between magnetic and non-magnetic assisted laser drilling process with respect to the material removal rate of drilled hole

It is observed that at a higher energy level, the taper angle value was reduced in laser drilling with the assistance of magnetic field (Fig. 5). This result is due to the expansion of gyration radius of plasma plume. This gyration radius mainly depends on the electron mass of the plasma plume. At lower energy level, the amount of plasma generated was minimum because less material removal from the hole. This low electron mass affects the gyration radius to minimum value. It acts as a shield to the forthcoming laser beam leads to reduction in laser beam intensity. For this reason, the taper angle value was higher in laser drilling with the assistance of magnetic field. The convergence effect of the laser beam was the primary reason for taper angle formed in the laser drilled hole.

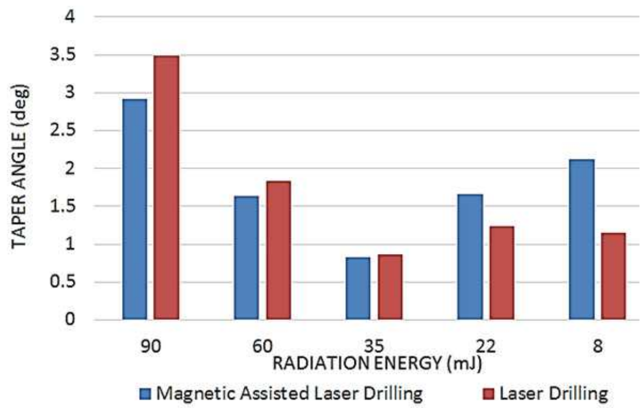

Fig. 5. Comparison between magnetic and non-magnetic assisted laser drilling process with respect to taper angle of drilled hole

It is observed that the spatter height value was reduced with the assistance of magnetic field. At higher energy level, the gyration radius of the plasma plume was high. Due to that the shielding effect of plasma was reduced to the forthcoming laser beam. So the laser intensity was high in this energy level. This leads to more vaporization of material in the process. Vaporization causes the material volume in the drilled hole to increase suddenly, creating high pressure. The vapour pressure (recoil pressure) expels the molten material from the hole. This effect illustrated in Figures 6,7. The amount of material removed from the hole will be high compared to laser drilling without the assistance of the magnetic field was shown in Figure 7. But the spatter height was high in laser drilling without the assistance of magnetic field showed in Figure 6. The reason for this effect was due to the less recoil pressure. Figure 8 show comparison between magnetic and non-magnetic assisted laser drilling process with respect to spatter height of drilled hole.

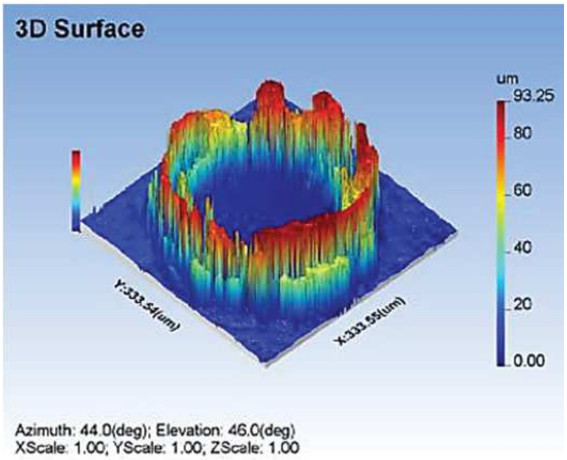

Fig. 6. 3D surface profile, spatter height of laser drilled hole entry side

From the Figure 9, it is clearly showing the defects such as barrelling and resolidified layer in the sidewall of the hole and in the entry side of the hole that is spatter. At the same time, Figure10, shows the better quality hole than the laser drilled hole without the assistance of magnetic field. The reason for this effect was due to the less recoil pressure and the kind of material removal mechanism. In laser drilling without the assistance of magnetic field, the laser intensity drop occurs due to shielding effect of plasma plume. This reduction in laser intensity leads to material removal mainly by melting. In magnetic assisted laser drilling, material removal is mainly due to vaporization of material from the hole.

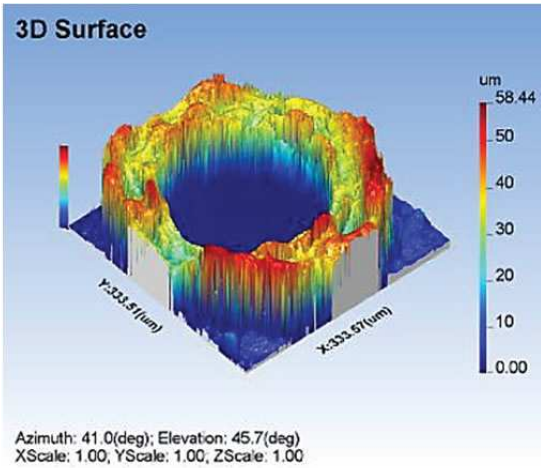

Fig. 7. 3D surface profile, spatter height of magnetic assisted laser drilled hole entry side

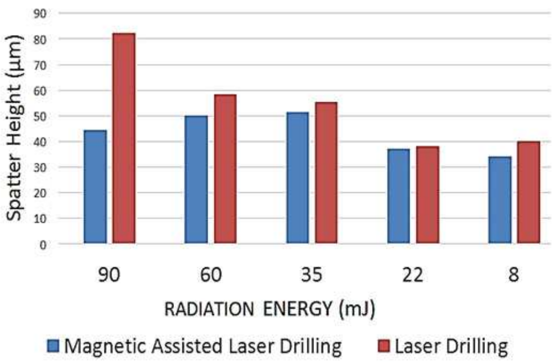

Fig. 8. Comparison between magnetic and non-magnetic assisted laser drilling process with respect to spatter height of drilled hole

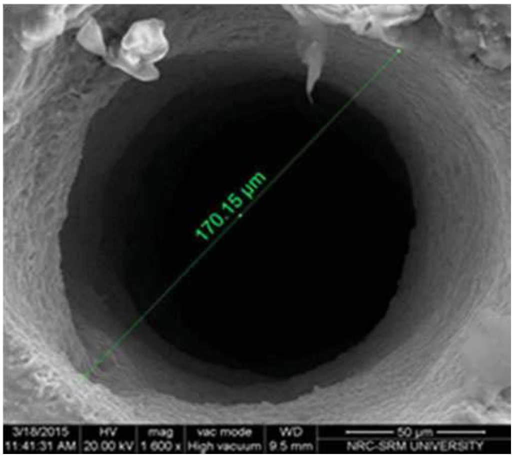

Fig. 9. SEM of non-magnetic assisted laser drilled hole

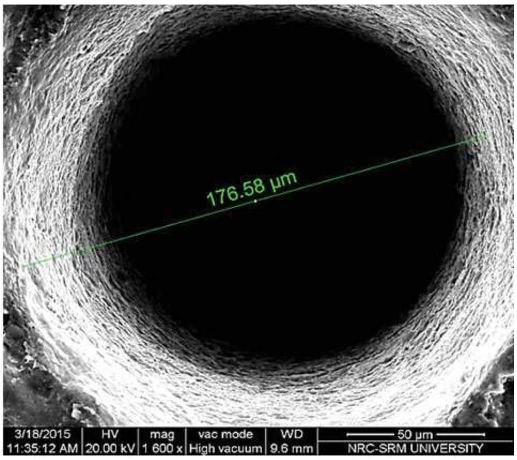

Fig. 10. SEM of magnetic assisted laser drilled hole

4. Conclusions

This work showed the possibility of using a magnetic field for influencing the nature of the plasma plume during laser drilling. The defect of percussion laser drilling that is barrelling effect in the drilled hole was reduced with the assistance of magnetic field setup. For the laser energy of 90 mJ, the Magnetic assisted laser drilling shows better improvement in the Material Removal Rate of 64.5%, the profile error that is spatter height was reduced to 45% and the Taper Angle of the drilled hole also reduced by 16.3%. This improvement showed the fact that the Lorentz force confined the plume particle to be raised upwards and circulated outwards to the sidewall from the centre of the laser beam. This expansion of laser induced plasma plume improved the material removal rate of the hole. Whereas, the hindrance effect of the plasma could be high when the laser radiation energy was reduced to 22 mJ, and the Taper Angle increased in the magnetic assisted laser drilling. The incorporation of Magnetic field to the laser drill needs a cost less setup, which can ensure reliable improvement in the MRR, Taper Angle and the profile error. Thus, the overall form of the drilled hole is improved by implementing the magnetic field setup.

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